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Supplementary Materials for

Contrasting processes driving tropical and non-tropical winter warm spells

Sijia Wu¹, Ming Luo^{1*}, Manqing Shi¹, Yu Tang¹, Tuantuan Zhang², Qiuting Wang¹, Xiaoyu Wang¹

1. School of Geography and Planning, and Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, Sun Yat-sen University, 510006, Guangzhou, China.
2. School of Atmospheric Sciences, Sun Yat-sen University; Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), 519082, Zhuhai, China.

*Correspondence: luom38@mail.sysu.edu.cn.

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Table S1. Contributions of different heating terms to winter warm spells across globe and different climate zones

Contributions	Global	Tropical	Non-tropical	Arid	Temperate	Polar	Cold
Advection heating	0.09	-0.13	0.12	-0.06	0.12	0.06	0.28
Adiabatic heating	1.09	-0.41	1.34	0.19	0.01	5.98	1.24
Diabatic heating	7.80	1.90	8.82	5.29	4.90	12.62	11.72
Net surface shortwave radiation	0.54	3.42	0.05	0.46	0.52	-0.21	-0.37
Surface downward longwave radiation	8.94	1.25	10.26	5.41	5.92	15.79	13.79
Surface latent heat flux	-0.26	-1.03	-0.13	0.37	-0.33	0.10	-0.51
Surface sensible heat flux	1.30	-1.04	1.70	0.90	1.60	1.39	2.44
Ground heat flux	-2.72	-0.70	-3.06	-1.86	-2.81	-4.46	-3.63

Table S2. Definitions of warm spell metrics

Metric (unit)	Definition
Frequency (event)	Yearly number of warm spell events
Participating days (day)	Yearly sum of participating warm spell days
Maximum duration (day)	Length of the longest yearly events
Mean duration (day)	Average length of all yearly events
Maximum intensity (°C)	Maximum intensity (temperature exceedance relative to the winter climatological mean) of all yearly events
Mean intensity (°C)	Average intensity of all yearly events

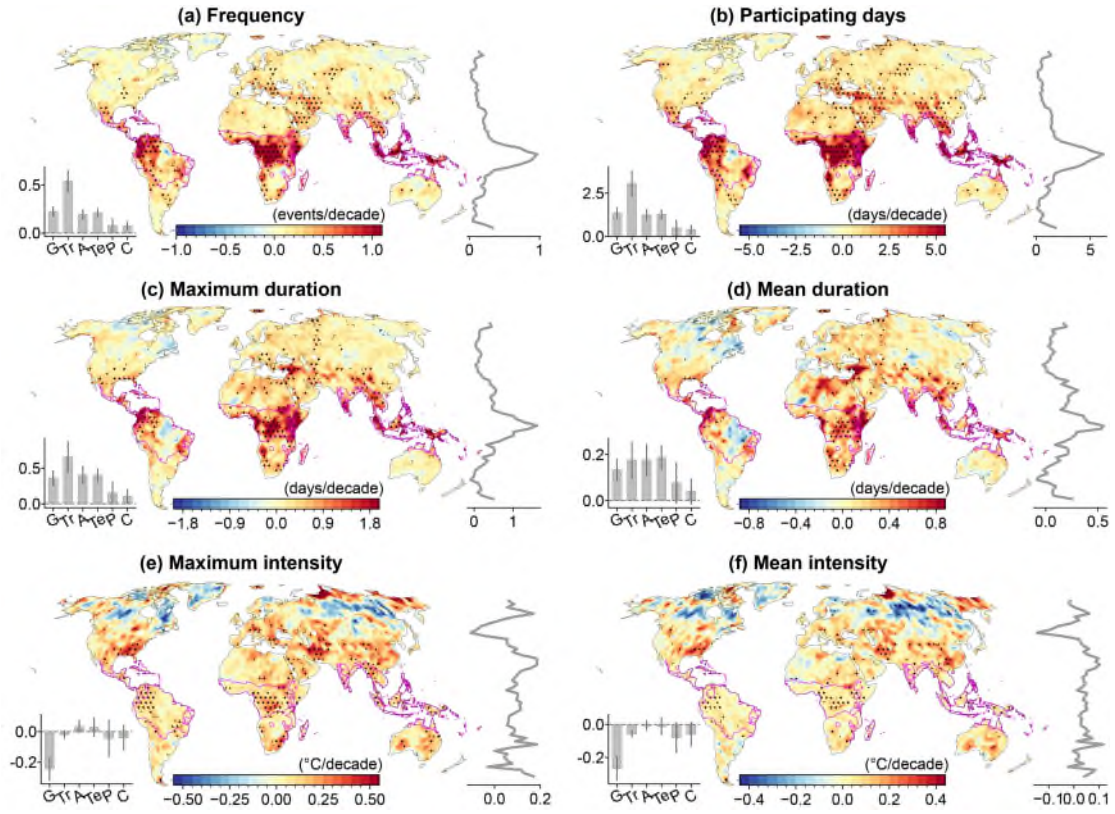


Fig. S1. Spatial distribution of the long-term trends of global winter warm spells. **a–f**, Maps showing the long-term trends of the frequency **(a)**, participating days **(b)**, maximum duration **(c)**, mean duration **(d)**, maximum intensity **(e)**, and mean intensity **(f)** of winter warm spells over global land areas during 1979–2023. The embedded bar chart shows the magnitude of the long-term trends of the corresponding characteristics with the black line encompassing its 90% confidence interval in different climate zones (G: global, Tr: tropical zone, A: arid zone, Te: temperate zone, P: polar zone, and C: cold zone). The latitudinal curves accompanying the maps show the zonal means of the trends of the corresponding characteristics.

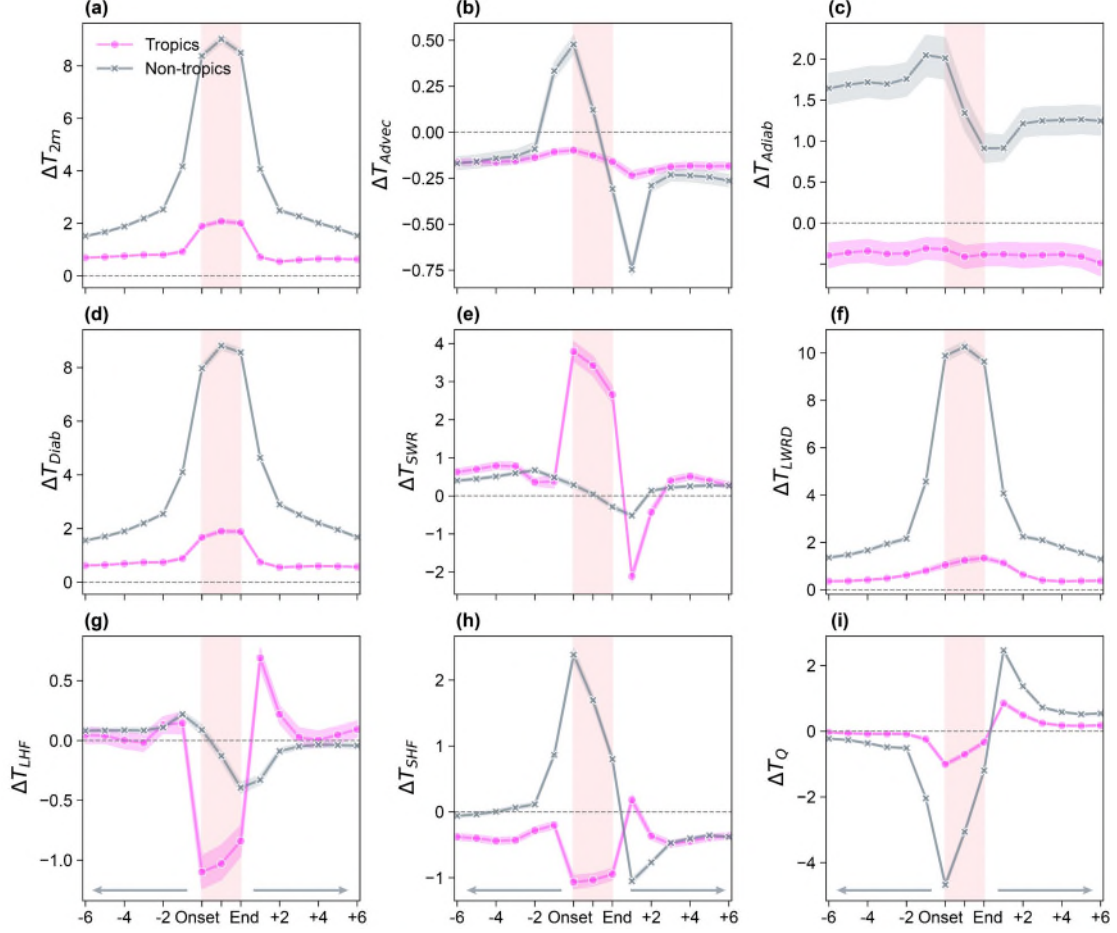


Fig. S2. Daily evolution of the regional mean of decomposition of temperature anomalies associated winter warm spells. **a**, The daily evolution of the regional mean of temperature anomalies of winter warm spells over global land areas during 1979–2023. **b–d**, The daily evolution of the regional mean of decomposition of temperature anomalies into the contributions of advection heating (**b**), adiabatic heating (**c**), diabatic heating (**d**). **e–g**, The decomposition of diabatic heating term into the contributions of net surface shortwave radiation (**e**), surface downward longwave radiation (**f**), surface latent heat flux (**g**), surface sensible heat flux (**h**), and ground heat flux (**i**) from 6 days before the onset to 6 days after the end of identified winter warm spells in the tropics (pink line) and non-tropics (grey line). Note that the label “Onset” denotes the day when the warm spell event starts, “– 2” denotes two days before the onset, and so on; “End” denotes the day when the warm spell event ends, “+2” denotes two days after the end, and so on.

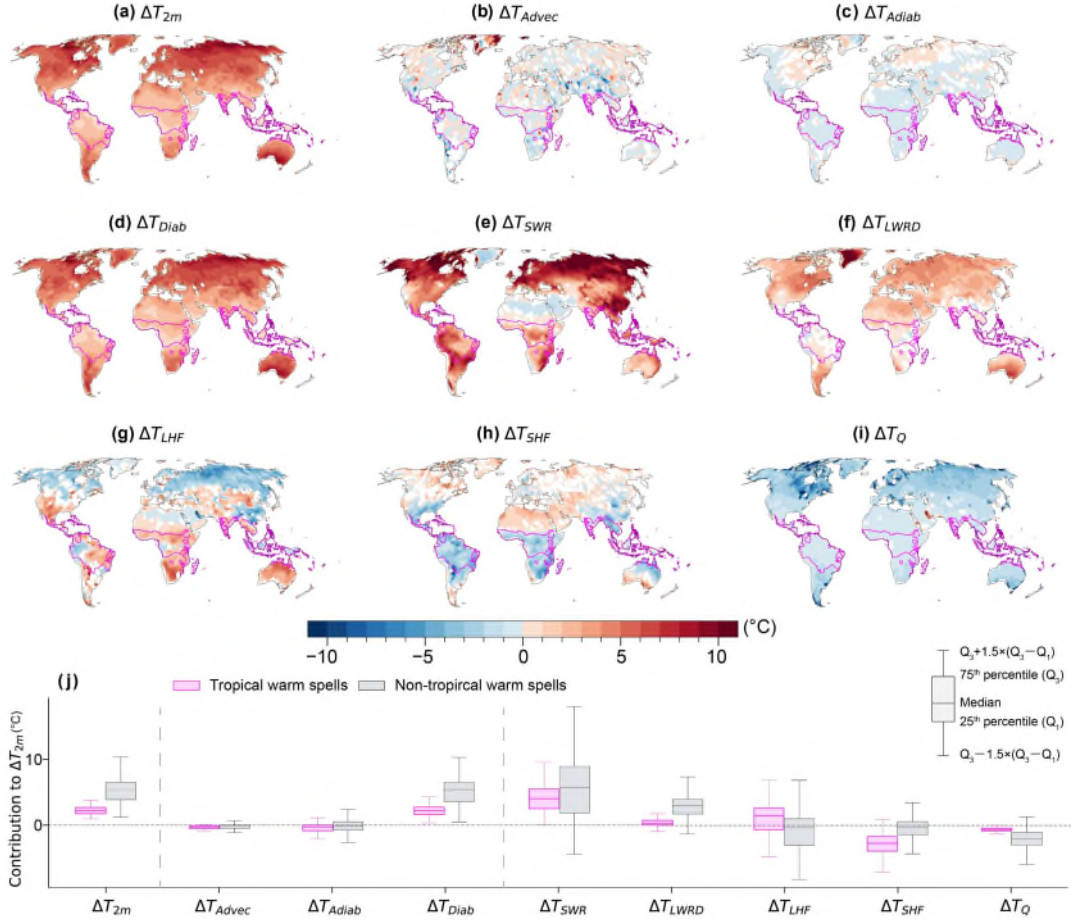


Fig. S3. Decomposition of temperature anomalies during summer heatwaves. a, Temperature anomalies of summer heatwaves over global land areas during 1979–2023. **b–d,** The decomposition of temperature anomalies into the contributions of advection heating (b), adiabatic heating (c), diabatic heating (d). **e–g,** The decomposition of diabatic heating term into the contributions of net surface shortwave radiation (e), surface downward longwave radiation (f), surface latent heat flux (g), surface sensible heat flux (h), and ground heat flux (i). Regions with the composite mean not passing the 0.1 significance level by the Student's *t*-test are masked out. **j,** Boxplot showing the regional mean of the temperature anomalies and its decomposition into the contribution of different heating terms to summer heatwaves in the tropics (pink bar) and non-tropics (grey bar). The centerline indicates the median value, the box bounds depict the 25th and 75th percentile values and the whiskers indicate the lower and upper quartiles ± 1.5 times the interquartile range of the decomposition of temperature anomalies.

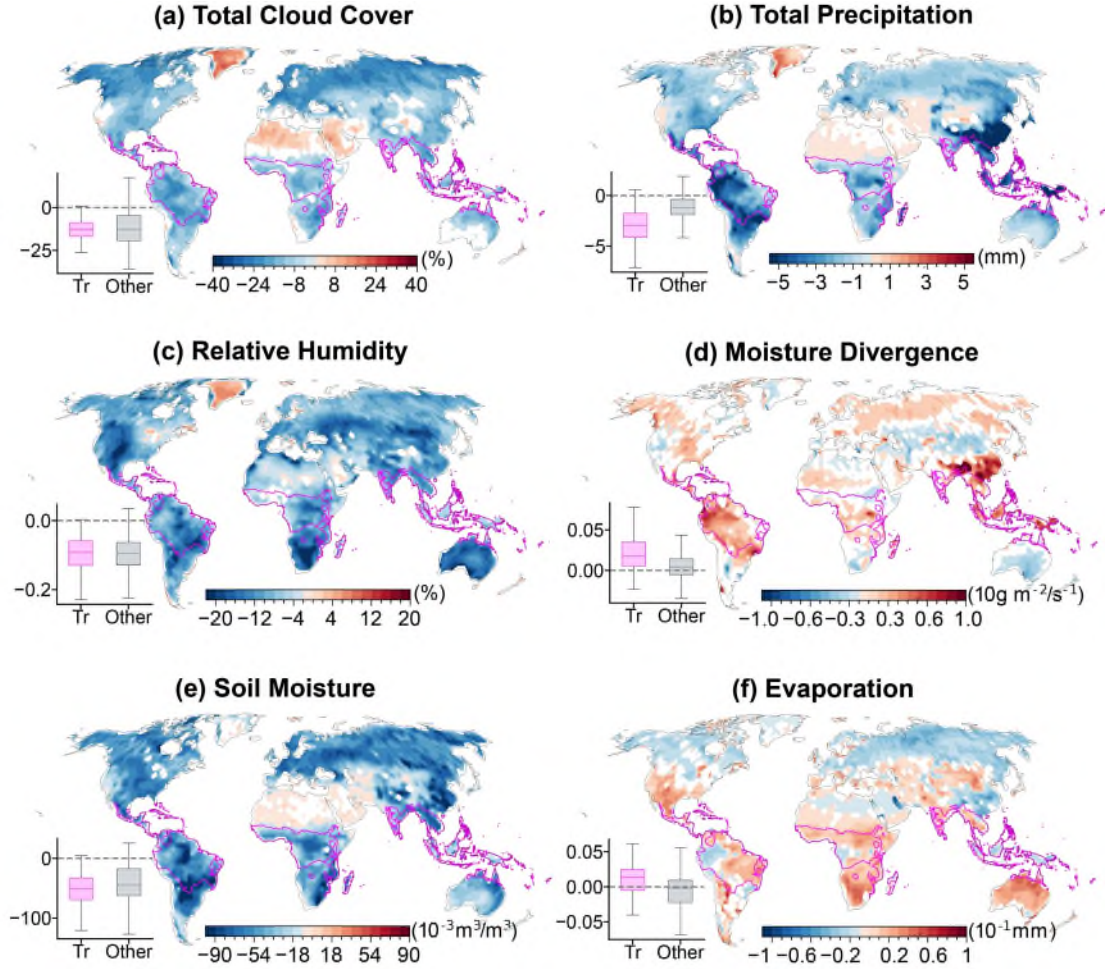


Fig. S4. Composite anomalies of key variables associated with summer heatwaves. **a–f**, The composite mean anomalies of total cloud cover (a), total precipitation (b), relative humidity (c), moisture divergence (d), soil moisture (e), and evaporation (f) associated with summer heatwaves. Regions with the composite mean not passing the 0.1 significance level by the Student's *t*-test are masked out. The embedded boxplot chart shows the regional mean of the anomalies of corresponding variables associated with heatwaves in the tropics (pink bar) and non-tropics (grey bar). The centerline indicates the median value, the box bounds depict the 25th and 75th percentile values and the whiskers indicate the lower and upper quartiles ± 1.5 times the interquartile range of the composite mean anomalies.

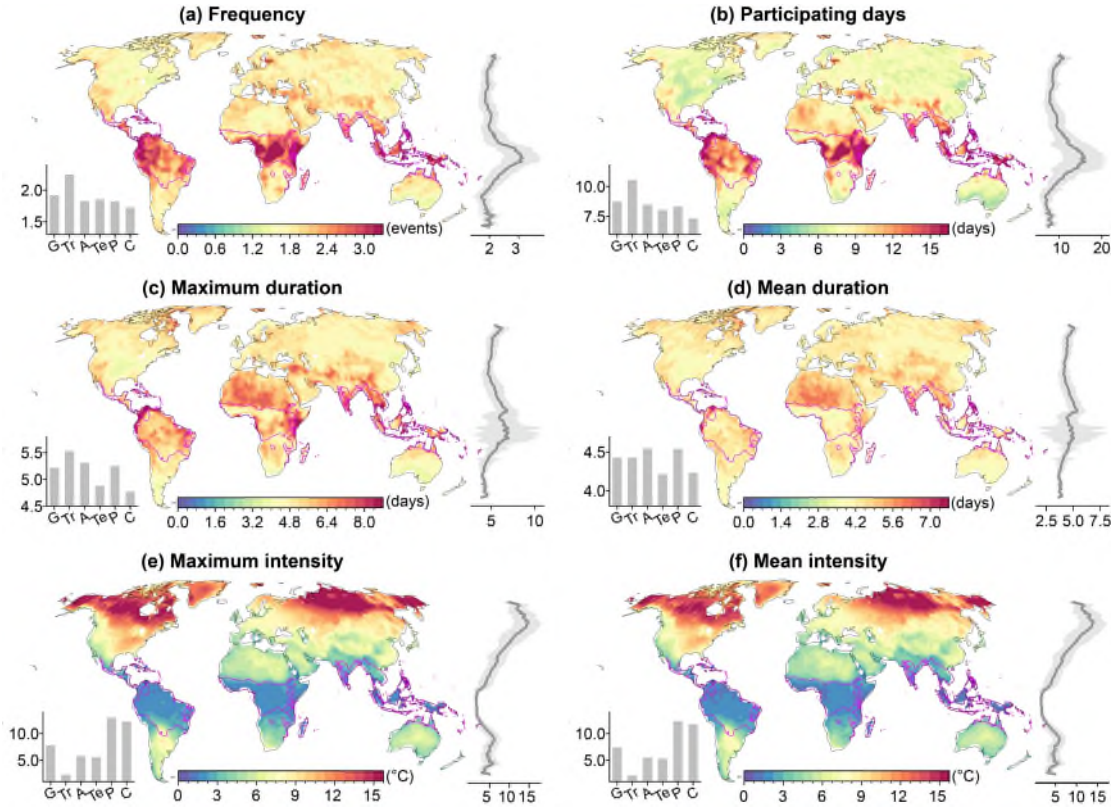


Fig. S5. Observed climatology of global winter warm spells at the $1^{\circ}\times 1^{\circ}$ resolution. **a–f**, Maps showing the climatological mean of annual mean frequency (**a**), participating days (**b**), maximum duration (**c**), mean duration (**d**), maximum intensity (**e**), and mean intensity (**f**) of winter warm spells over global land areas during 1979–2023. The embedded bar chart shows the climatology of the corresponding characteristics in different climate zones (G: global, A: arid zone, Te: temperate zone, Tr: tropical zone, P: polar zone, and C: cold zone). The latitudinal curves accompanying the maps show the zonal means of the climatology of the corresponding characteristics, and the shading indicates the spread of zonal mean values (mean $\pm$ *s.d.*).

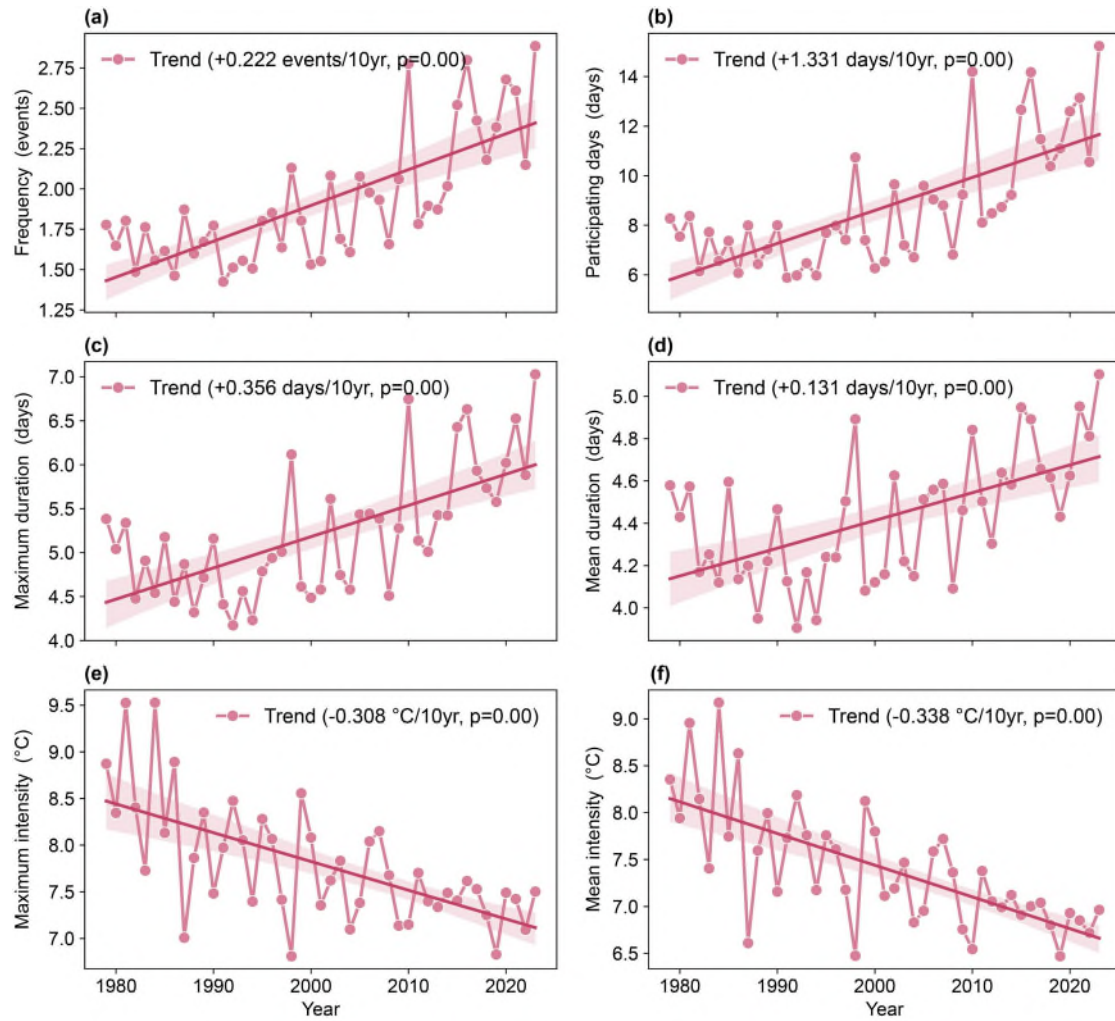


Fig. S6. Long-term changes of global winter warm spells at the $1^{\circ}\times 1^{\circ}$ resolution. **a–f**, Time series of the spatially-averaged annual mean of frequency (a), participating days (b), maximum duration (c), mean duration (d), maximum intensity (e), and mean intensity (f) of warm spells over global land areas from 1979 to 2023. The straight line indicates the linear trend, and the shading indicates the corresponding 90% confidence interval. Slope and p -value estimates for the trend per decade are given in parentheses.

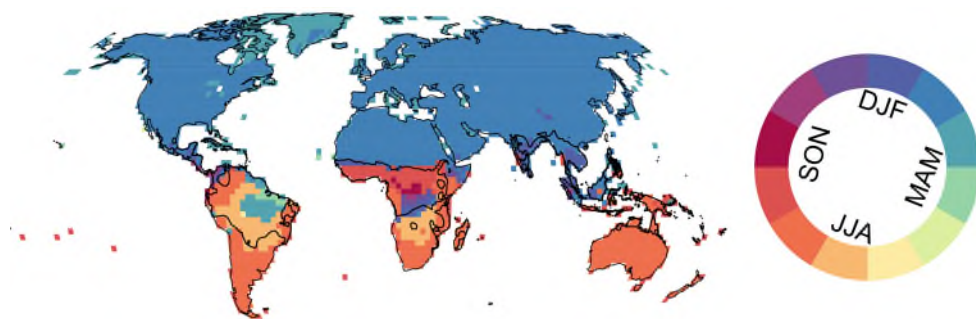


Fig. S7. Spatial distribution of the cold season.

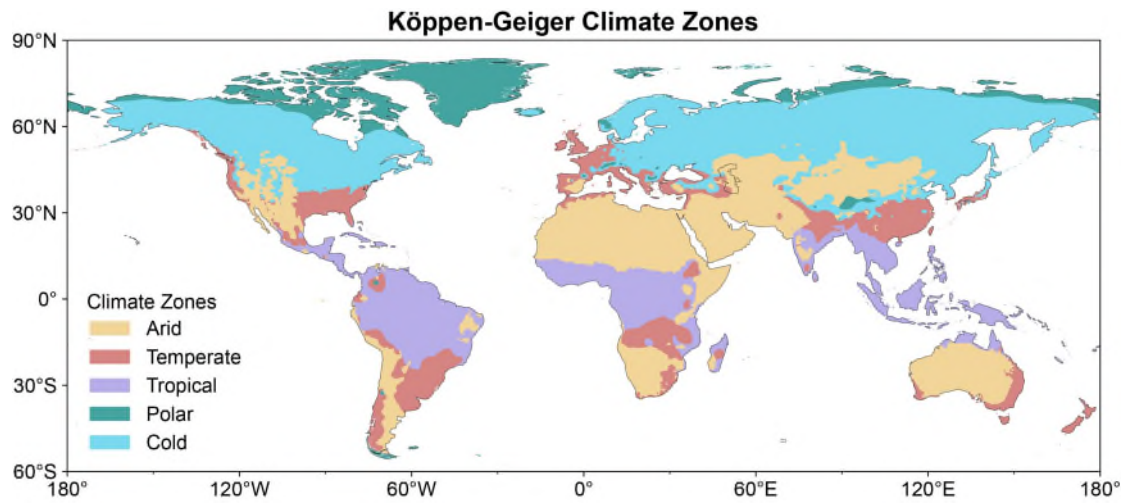


Fig. S8. Köppen-Geiger climate zones including arid, temperate, tropical, polar, and cold zones.